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## SNOW HYDROLOGY FOR MULTIPLE-PURPOSE RESERVOIRS

By Herbert S. Riesbol, M. ASCE

HYDRAULICS DIVISION

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PAPERS

# SNOW HYDROLOGY FOR MULTIPLE-PURPOSE RESERVOIRS

By Herbert S. Riesbol,[1] M. ASCE

## Synopsis

Snow is a form of precipitation possessing certain characteristics which can be evaluated and applied to advantage, both from an hydrologic and an economic viewpoint, in the planning and design of multiple-purpose storage reservoirs. This paper describes briefly the processes of snow melting and runoff, and presents criteria and examples of procedures followed in applying the knowledge of these processes to determine reservoir space allocations and spillway capacities. The writer calls attention to the gap existing between detailed physical knowledge of evaporation and melting processes and application of this knowledge to practical design problems.

## Introduction

Hydraulic engineers responsibie for planning and designing multiple-purpose storage reservoirs recognize snow as a form of precipitation possessing certain characteristics which can be evaluated and applied to advantage, from both an hydrologic and an economic viewpoint. In northern latitudes and at high elevations, snow falls and accumulates on the earth's surface in frozen crystalline form and usually remains until a proper sequence of meteorologic events provides the thermodynamic conditions essential for either evaporation or melting. Periodic snow surveys provide a reliable index of the relative snow accumulation. With knowledge of the processes of storage, evaporation, and melting, the engineer can predict, with reasonable accuracy (for normal climatic conditions and for a known snow pack), the characteristics and amount of stream flow to be expected. These predictions are then applied in determining multiple-purpose reservoir capacities and in designing spillways. In contrast, forecasts of amounts of rainfall can at best be made only a few

Note.—Written comments are invited for publication; the last discussion should be submitted by November 1, 1953.

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hours before the actual storm, and runoff occurs almost immediately after the rain has fallen.

In the United States the greatest total snowfall and accumulation occur in the high mountain areas and extreme northern latititudes. In the western states, the economy of the arid and semi-arid lands lying between the mountain ranges is increasingly dependent on development of multiple-purpose storage reservoirs to utilize the stream flow originating in the high mountain snow packs. Engineers of the western states accept as a blessing the fact that the predictable characteristics of this stream flow enable economies in planning and designing multiple-purpose reservoirs by the joint use of space allocated to the various functions and by the reduction of spillway capacities. They continually seek fuller understanding of the processes of snow evaporation, melting, and runoff, and of their application to determining reservoir and spillway capacities as expressed in the following sections of this paper.

## Snow Evaporation, Melting, and Runoff

Snow has the desirable characteristic of being stored on the earth's surface for a considerable period of time before it evaporates, or melts and infiltrates into the soil, or runs off into stream channels (usually at a moderate rate). The snow cover, because of its structure, will store and hold considerable quantites of the rain which falls on it and will facilitate the infiltration of temporarily stored water into the underlying soil mantle. Thus, it tends to retard and regulate the runoff from excessively rapid precipitation. Runoff from snow melt is seasonal in occurrence, of long duration, of relatively large volume, and of moderate rate, and can be forecast in terms of total volume on the basis of snow surveys, precipitation, and temperature.

The melting and evaporation of a snow cover are fundamentally a matter of thermodynamics. Walter T. Wilson,[2] A.M. ASCE, has presented an admirable outline of the thermodynamic relationships. The sun is the ultimate source of energy. This heat energy can reach the snow through several indirect paths in the atmosphere and by direct radiation. For practical application, however, the temperature of the air seems to be the most significant single index of melting conditions. Snow-melt rates frequently are expressed as functions of air temperatures measured in degree-days above freezing. Such expression incorrectly implies that other effects are either negligible or constant, or that they are simple functions of temperature. The significant paths by which solar energy actually reaches the snow may be divided into two categories. The first category consists of three major paths: Radiation, convection or turbulent exchange, and condensation or latent heat. The second category is composed of three minor paths: Conduction from air, conduction from underlying soil, and warm rain. As melt occurs, the melt water accumulates in and moves through the snow pack in accordance with certain physical laws. Robert W. Gerdel,[3] M. ASCE, has studied and reported on these relationships in some detail.

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[2] "An Outline of the Thermodynamics of Snowmelt," by Walter T. Wilson, *Transactions*, Am. Geophysical Union, 1941, Pt. I, pp. 182–195.

[3] "The Dynamics of Liquid Water in Deep Snow Packs," by R. W. Gerdel, *ibid.*, Vol. 26, Pt. I, August, 1945, pp. 83–90.

Much has been accomplished in identifying the physical factors contributing to the processes of snow melting and evaporation, and in determining the intricate relationships existing among these factors. Regardless of these accomplishments, the engineer who must apply them in the planning and design stage finds that usually it is not practicable, with the hydrologic and meteorologic data available (1953), to apply all these factors and their relationships on a watershed basis. He is compelled, therefore, to utilize his knowledge of the physics of snow evaporation and snow melt largely as a guide to judgment, and to turn to empirical relationships which make use of available data when he is performing his computations. As a backlog of data covering the various pertinent hydrologic and meteorologic factors becomes available, it will be possible to apply the results of research and to obtain a more precise and economic design.

The problem of predicting the shape of the snow-melt hydrograph is usually approached from the premise that, with a full snow cover, an excess of 1° of

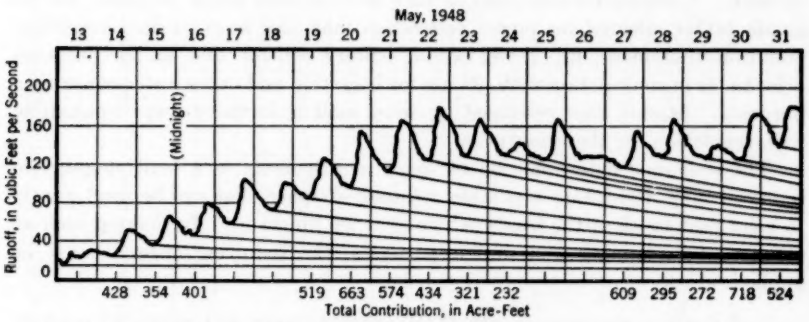


FIG. 1.—SNOW-MELT RUNOFF, ST. LOUIS CREEK NEAR FRASER, COLO. (AREA 32.8 SQ. MILES)

temperature above a given base (usually 32° F) would produce a constant volume of runoff.

It has been demonstrated by W. U. Garstka,[4] M. ASCE, and others, working with relatively complete data from an experimental watershed in the Fraser Experimental Forest in the Rocky Mountains of Colorado, that the melt from one day of temperature excess will reach a peak within a certain lag time, after which the remainder of the runoff will follow a recession curve having a fairly constant slope factor, as shown in Fig. 1, in which the total contribution to runoff made by the day's snow melt has been computed from a recession-curve analysis of the hydrograph. In this connection, it is recognized that the runoff is divided into three components: (1) Overland flow directly into stream channels; (2) subsurface flow through the mantle of decayed vegetation and soil; and (3) ground-water flow from ground-water tables in the underlying rock. Overland flow usually is reflected in the immediate daily peak of the hydrograph, and subsurface and ground-water flow

[4] "Report No. 1, the 1948 Snowmelt Season, Progress in Snow Investigations at the Fraser Experimental Forest," Cooperative Snow Investigations, prepared and published jointly by the Bureau of Reclamation, U. S. Dept. of the Interior, and Forest Service, U. S. D. A., November, 1949.

are reflected in the recession curve—the change in dominance from one to the other appearing as a change in slope. Application of this knowledge permits an analysis somewhat similar to the approach based on the unit hydrograph and recession curve, as commonly used in the development of stream-flow hydrographs from rainfall.

## Capacities of Multiple-Purpose Reservoirs

In multiple-purpose reservoirs, storage capacities allocated to such functions as irrigation, hydroelectric power generation, flood control, and navigation are determined by operation studies in which historical stream flows are regulated to satisfy the multiple requirements. The historical stream flows are derived either from recorded discharge measurements, or, if necessary, by correlation with recorded stream flows or other data in the same climatic and physiographic area. Water-storage requirements are determined by studying demands of the various multiple uses after unregulated sources have been utilized. A release for one purpose may serve several other purposes; for example, water released for power generation may also be used for navigation, pollution abatement, fish preservation, salinity control, and similar purposes prior to, or in conjunction with, its use for irrigation and other water-consuming purposes. Stream flow produced by snow melt is in many ways compatible with regulation for these purposes.

The economic determination of space requirements in a multiple-purpose reservoir may depend on a reliable estimate of space that can be used jointly to meet part or all of the needs of two or more functions. In making such an estimate for planning and design purposes, the following criteria must be applied:

*a.* Irrigation storage capacity (both single-purpose and joint-use) must be filled during the runoff season. Favorable allowance is made for probable overestimate of the forecasted seasonal runoff.

*b.* Flood-control storage capacity (both inviolate and joint-use), as required for the control of the predicted flood at any time during a given season, must be definitely available on the specified date. Necessary allowance is made for probable underestimate of the forecasted flood runoff.

*c.* Water for power, as required—in addition to usable irrigation and other functional releases for generation of prime power to meet contract schedules throughout the year—must be stored entirely during the runoff season.

*d.* If storage requirements are also established for other functions, such as pollution and salinity control, criteria must be applied.

The key feature of reservoir operating plans involving joint use of storage for irrigation and flood control, or variable allocations to flood control, is the set of operating curves commonly called operation "parameters." In Fig. 2 an example of these operating parameters is shown for the Palisades Reservoir on the Snake River, in southeastern Idaho. They show anticipated runoff from any given date until July 31. A typical method for deriving and applying these parameters will be outlined briefly, omitting details. Similar procedures,

suited to the stream-flow characteristics of other basins, are "tailor-made" to meet the particular situation.

*Runoff Forecasting Curves.*—These curves are the first essential feature of a reservoir operating plan based on variable allocations to flood control. The curves can be derived only when the basic data are adequate for reliable corre-

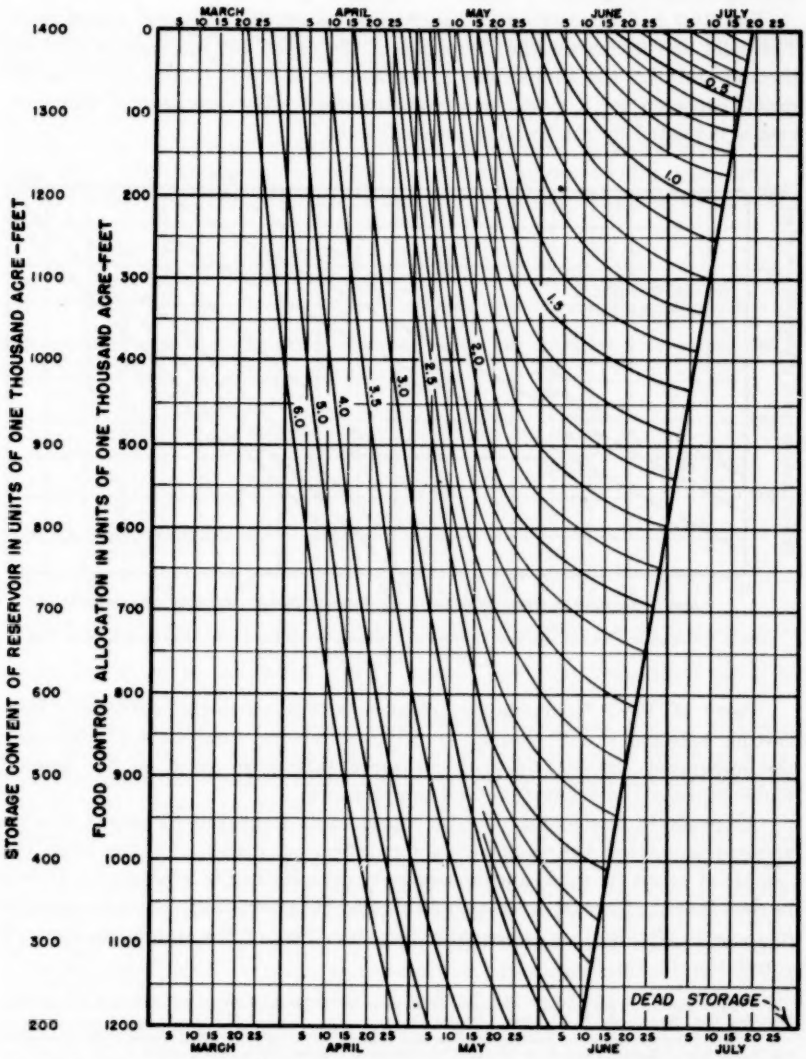


FIG. 2.—ALLOCATION OF FLOOD-CONTROL SPACE ON THE BASIS OF ANTICIPATED FLOOD-SEASON RUNOFF. (PARAMETERS ARE IN MILLIONS OF ACRE-FEET)

lations between snow indices and natural runoff at the potential reservoir site. Reliable, seasonal runoff forecasts are limited at the present time to streams deriving most of their flood-producing runoff from snow melt during the spring and early summer months. James E. Church,[5] a leader and early pioneer in the field of snow surveying and runoff forecasting, has done much excellent writing on the subject.

Fig. 3(*a*) is a forecast curve based on snow survey data and runoff data. The solid line represents the regression of the runoff for the months of April through July on the snow-water equivalent as of April 1, and indicates the runoff expected for a given snow measurement. The precision of the forecast is indicated by the limiting (dashed) lines.

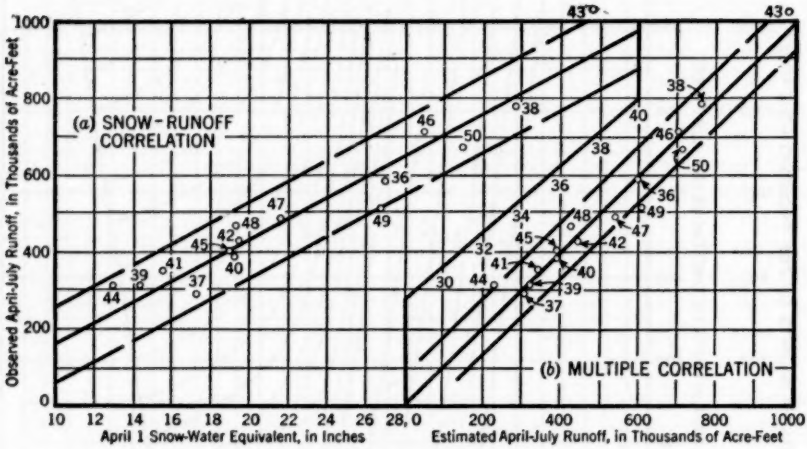


FIG. 3.—FORECAST CURVES FOR THE SOUTH FORK OF THE BOISE RIVER AT ANDERSON RANCH DAM NEAR BOISE, IDAHO

Perry M. Ford[6] has made important contributions to the methods of forecasting seasonal runoff through multiple-correlation analysis for evaluating the integrated influence of such measured factors as snow on the ground (snow surveys[7]), precipitation, and temperature.

Accuracy in forecasting may be considerably improved by means of a regression involving the multiple factors affecting runoff. In Fig. 3(*b*) the ombined effect of snow and antecedent precipitation is evaluated. It will be seen that the forecast error, as indicated by the probability limits comparable to those in Fig. 3(*a*), is appreciably less than that of the simple snow-runoff correlation in Fig. 3(*a*).

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[5] "Snow and Snow Surveying," by James E. Church, in "Hydrology," Oscar E. Meinzer, Dover Publications, Inc., New York, N. Y., 1949, Chapter IV.

[6] "Multiple Correlation in Forecasting Seasonal Runoff," by Perry M. Ford, *Engineering Monograph No. 2*, Bureau of Reclamation, U. S. Dept. of the Interior, Denver, Colo., April, 1949.

[7] "Snow Surveying," by James C. Marr, *Miscellaneous Publication No. 380*, U. S. D. A., Washington, D. C., June, 1940.

In Fig. 3 the encircled points are identified by the last two digits in the applicable year. The values of the snow-water equivalent represent averages as of April 1 covering the period of record for five snow courses in Idaho. The forecast derived from Fig. 3(*b*) is based on conditions of April 1, 1950. The equation for the solid-line curve in Fig. 3(*a*) is

$$y = 26.89\,x - 95.53 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which $x$ represents abscissa values and $y$ represents ordinates. The solid-line curve in Fig. 3(*b*) may be expressed as

$$y = 17.0\,x_2 + 21.4\,x_3 - 126.0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which, for the forecast of April 1, 1950, $x_2$ is the precipitation observed from October, 1949, through January, 1950, and $x_3$ is the snow-water equivalent of April 1, 1950. In Fig. 3(*a*) the dashed-line limits have departures from the

TABLE 1.—ANALYSIS OF AN HISTORICAL FLOOD

| Period (1) | Volume[a] (2) | Summation[a] (3) | Volume[a,b] (4) | Summation[a,b] (5) |
|---|---|---|---|---|
| Feb. 1–15 | 94.4 | 4,382.6 | | |
| 16–28 | 87.0 | 4,288.2 | | |
| March 1–15 | 93.5 | 4,201.2 | | |
| 16–31 | 126.8 | 4,107.7 | | |
| April 1–15 | 122.9 | 3,980.9 | −477.1 | 0 |
| 16–30 | 239.1 | 3,858.0 | −360.9 | 200.2 |
| May 1–9 | 296.2 | 3,618.9 | −63.8 | 561.1 |
| 10–15 | 297.4 | 3,322.7 | 57.4 | 624.9 |
| 16–31 | 1,135.7 | 3,025.3 | 495.7 | 567.4 |
| June 1–7 | 351.8 | 1,889.6 | 71.8 | 71.8 |
| 8–15 | 278.6 | 1,537.8 | | |
| 16–30 | 514.4 | 1,259.2 | | |
| July 1–15 | 454.7 | 744.8 | | |
| 16–31 | 290.1 | 290.1 | | |

[a] In thousands of acre-feet. [b] For runoff greater than 20,000 cu ft per sec.

mean line equal to ± 98,200 acre-ft; and in Fig. 3(*b*), departures equal to ± 79,450 acre-ft.

*Analysis of Historical Floods.*—In developing parameters, each historical flood at the reservoir site is analyzed to determine the storage space required, to control that flood to a specified maximum release (usually the nondamaging downstream channel capacity), at the same time, having the reservoir at the maximum safe level at the end of the flood season. In that regard it is necessary to have the following basic information: The maximum release through outlets at the dam (normally equal to the safe channel capacity at critical downstream points); the active storage capacity of the reservoir; the daily discharges for significant floods of record (care having been taken to include relatively small floods occurring either early or late in the snow-melt season as these floods may prove valuable as control points); and the date when snow-melt inflow generally becomes negligible.

Each flood also is analyzed to determine the storage space required at various time intervals to limit the flood to the specified maximum release. In

Table 1 the procedure is illustrated by a hypothetical example in which the maximum release is 20,000 cu ft per sec; the end of the snow-melt period is July 31; the routing time interval, 15 days; the active storage capacity 1,200,000 acre-ft; and daily discharge data are available. After the flood-storage requirements are computed for each flood, the storage requirement volumes are plotted against time.

Daily discharges were analyzed for selected periods shown in Col. 1, Table 1. All intermediate periods were chosen as 15-day or 16-day periods excepting the period from May 1 to May 9, which was selected from daily records because the snow-melt runoff began to exceed the channel capacity on May 10, and the period from June 1 to June 7, which was selected from daily records to be the end of the flood season.

The summations of daily discharges exceeding 20,000 cu ft per sec during each period are converted in Col. 4, Table 1, to thousands of acre-feet. Negative volumes indicate periods when drawdown could be made and show how much can be released within the safe channel capacity. When daily flows begin to exceed the safe channel capacity, water must be stored. Minor rises above channel capacity, followed by periods of flow below channel capacity, are disregarded.

For example in Table 1, drawdown was required beginning on April 9, storage was required beginning on May 10, and the flood storage was completed on June 7, after which the daily discharge remained below 20,000 cu ft per sec. The summation of Col. 4, Table 1, from June 7 backward through April 9, as listed in Col. 5, shows the amount of storage space necessary at the beginning of each period to control the flood of Col. 2 to a release of 20,000 cu ft per sec. The April 9 date was determined by an analysis of daily records showing that the total of daily flows under 20,000 cu ft per sec was 200,200 acre-ft between April 15 and April 9.

After the flood-storage requirements have been computed for each flood, the storage requirement volumes (Col. 5, Table 1) are plotted against time. For the example presented in Table 1, the plotting would consist of the follow-data, in thousands of acre-feet:

| Date | Flood-control reservations | Remaining flood volume |
|---|---|---|
| April 9 | 0 | 3,900 |
| April 16 | 200.2 | 3,900 |
| May 1 | 561.1 | 3,600 |
| May 10 | 624.9 | 3,300 |
| May 16 | 567.5 | 3,000 |
| June 1 | 71.8 | 1,900 |

The dates would be plotted as the abscissa values, and the ordinates would be the flood-control reservations. The remaining flood volumes are indicated by a third set of variables (see the family of curves in Fig. 2).

The next step is to draw curves that envelope critical points. These curves, drawn for selected parameter intervals and smoothed for continuity and spacing without changing their enveloping characteristics, are the oper-

ating parameters of the example shown in Fig. 2. The remaining flood volumes of the foregoing tabulation are the variables indicated by these curves.

Ordinarily the first drawing of the enveloping parameter curves will require some adjustment to assure ideal multiple-purpose operation. It is desirable to test the parameters by operating the reservoir through critical flood and drought periods, using the runoff forecasting curves and the parameter curves under simulated operating conditions. Frequently, daily operation is necessary during critical periods. This testing and adjustment of the parameters is particularly beneficial to irrigation interests. In many cases, permissible adjustments can be made in the lower (right-hand) part of the parameters, permitting greater storage contents at the end of the snow-melt season.

The operating plan for reservoirs for which variable flood-control allocation are to be made should be, essentially, a set of general regulations covering application of the operating parameters. Technical detail should be kept to a minimum, and matters of basic operating policy should be paramount. The actual forecast curves and operation parameters are subject to continual revision on the basis of new data and experience.

## Application to Spillway Design

The spillway and surcharge storage capacity for any dam and reservior project are determined by the inflow design flood. This flood may be from snow melt, rainfall, or a combination thereof, depending on the source area. The inflow design flood usually is equal to the maximum probable flood. The maximum probably flood is defined as the largest flood that can be reasonably expected on a given stream at a selected point, and is distinguished from the maximum possible flood by rational consideration of the chance of simultaneous occurrence of the maximum (or minimum) of the several elements or conditions contributing to the flood.

The practical determination of a maximum probable snow flood is at present (1952) generally dependent on empirical relationships derived from studies of observed runoff, precipitation, temperatures, and wind velocities, reapplied under the assumption of reasonable concurrence of maximum conditions. Empirical relationships and procedures to be applied vary with geographical location—with the size, elevation, and topography of the basin—and with the type and quantity of available hydrologic data.

The maximum probable snow flood may be generated by snow melt alone, or by a combination of snow melt and rainfall. The "combination" flood falls into one or the other of two categories—namely, the "rain-on-snow" flood and the "snow melt-followed-by-rain" flood. The first of these results from rain falling directly on the surface of the snow pack. The rain water is then transmitted either directly and rapidly through the snow pack to the underlying soil or rock surface, or it is absorbed within the snow pack. The absorbed water or prolonged storage with some concurrent melting of the snow continues until the combined rain water and melt water is released either as infiltration into the underlying soil and rock, or runs off into stream channels. Floods of the second category result from rain falling on the wetted soil left when the snow pack has melted. Runoff occurs according to normal rainfall-

runoff relationships. In this case, the rain flood usually "rides" downstream on the recession of the antecedent snow flood to form a secondary peak which may exceed the snow-flood peak in magnitude.

*Flood from Snow Melt Alone.*—Several recognized procedures exist for developing hydrographs for the maximum probable flood from snow melt alone, the selection of procedure depending on the location, the size, and the elevation of the watershed, and on the available hydrologic and meteorologic data. One procedure now (1952) being applied by the Bureau of Reclamation, United States Department of Interior (USBR), for developing the maxi-

TABLE 2.—Determination of the Relation Between Temperature and Snow-melt Runoff

| Year | Maximum 15-Day Runoff[a] | | Temperature Station A | | Melting rate of runoff, in inches per degree-day[e] | Total Snowmelt Runoff | |
|---|---|---|---|---|---|---|---|
| | (Cu ft per sec)-day | Inches | Accumulated[b] temperature[c] above 32° F | Degree-days adjusted to basin[d] | | (Cu ft per sec)-day | Inches |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 1944 | 39,610 | 4.91 | 294 | 234 | 0.0210 | 77,200 | 9.57 |
| 1942 | 26,460 | 3.28 | 266 | 206 | 0.0159 | 67,040 | 8.31 |
| 1941 | 25,250 | 3.13 | 376 | 316 | 0.0099 | 42,350 | 5.25 |
| 1938 | 22,760 | 2.82 | 269 | 209 | 0.0135 | 67,280 | 8.34 |
| 1937 | 32,670 | 4.05 | 360 | 300 | 0.0135 | 76,960 | 9.54 |
| 1936 | 28,880 | 3.58 | 259 | 199 | 0.0180 | 72,360 | 8.97 |
| 1935 | 56,950 | 7.06 | 305 | 245 | 0.0288 | 98,740 | 12.24 |
| 1933 | 53,160 | 6.59 | 374 | 314 | 0.0210 | 84,700 | 10.50 |
| 1932 | 40,170 | 4.98 | 392 | 332 | 0.0150 | 66,070 | 8.19 |
| 1931 | 30,010 | 3.72 | 294 | 234 | 0.0159 | 53,480 | 6.63 |
| 1930 | 26,780 | 3.32 | 230 | 170 | 0.0195 | 79,860 | 9.90 |
| 1929 | 27,750 | 3.44 | 251 | 191 | 0.0180 | 62,680 | 7.77 |
| 1928 | 45,980 | 5.70 | 289 | 229 | 0.0249 | 138,910 | 17.22 |
| 1926 | 46,870 | 5.81 | 329 | 269 | 0.0216 | 95,840 | 11.88 |
| 1925 | 37,430 | 4.64 | 420 | 360 | 0.0129 | 60,020 | 7.44 |
| 1924 | 53,320 | 6.61 | 264 | 204 | 0.0324 | 119,800 | 14.85 |
| 1923 | 51,060 | 6.33 | 292 | 232 | 0.0273 | 134,070 | 16.62 |
| 1922 | 47,520 | 5.89 | 353 | 293 | 0.0201 | 106,970 | 13.26 |
| 1921 | 77,120 | 9.56 | 337 | 277 | 0.0345 | 132,140 | 16.38 |

[a] The contributing area is 300 sq miles. [b] Over a 15-day period. [c] Daily mean, in degrees Fahrenheit. [d] The lapse rate is 4° per 1,000 ft. [e] Values in Col. 6 are found by dividing the runoff of Col. 3 by the degree-days of Col. 5.

mum probable snow flood for small areas located where the occurrence of rain on snow during the winter season is not probable, is demonstrated as follows:

1. The maximum experienced snow-melt runoff rates for the basin are computed either in inches, or in (cubic feet per second)-days, per degree-day of temperature, for the years in which little or no precipitation occurred during the period of high snow-melt runoff. Normally, during any one season, the period of high snow-melt runoff is confined to a period of from 10 days to 20 days. In the example shown in Table 2 a 15-day runoff period is used.

2. The part of the basin that will contribute to the snow-melt flood runoff is estimated from the approximate elevation of the snow line as observed during the maximum runoff period of record. The judgment of the engineer making the study is all-important. The aspect, exposure, and latitude of the watershed all have bearing on the selected elevation. It is assumed in this example

that 300 sq miles, of a total of 460 sq miles, above the proposed dam site, would contribute.

3. From a temperature station near to, and representative of, the basin, the accumulated degree-days of temperature above 32° F corresponding to each of the maximum 15-day runoff periods are computed and adjusted according to the mean change in temperature per 1000 ft of elevation (lapse rate) to the mean elevation of that part of the basin which contributes to the snow-melt runoff (see Table 2, Col. 4). If the stream-gaging station is a considerable distance from the snow-melt area, it is necessary to determine time lag between snow-melting temperatures and runoff.

4. The maximum 15-day runoff expressed in inches is divided by the accumulated and adjusted degree-days for the period to determine the melting rate of runoff.

5. For each year tabulated, the total runoff which occurred during the entire snow-melt season until the daily mean flow receded to the ground-water

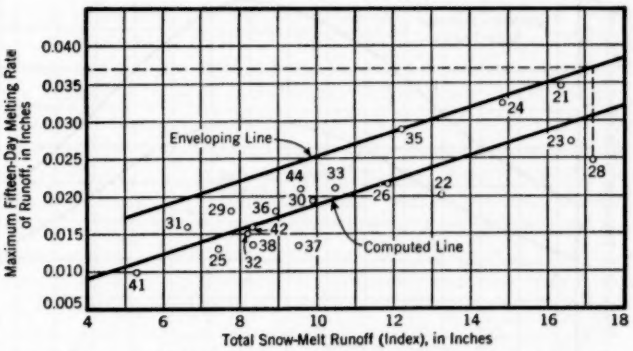


FIG. 4.—MAXIMUM 15-DAY MELTING RATE OF RUNOFF AS RELATED TO THE TOTAL SEASONAL SNOW-MELT RUNOFF

recession curve (see Table 2, Col. 8) is computed in inches. This is the "index" runoff.

6. The melting rate of runoff (in inches per degree-day) for each selected annual 15-day period is plotted against the index runoff (see Fig. 4). A mean line through these points is computed using the method of least squares, and an enveloping line is drawn through the maximum point, parallel to the computed line. The slope of the computed line in Fig. 4 is 0.00165 in. per in., and the vertical intercept is 0.00257 in.

7. In the example shown in Fig. 4, the year of greatest runoff from snow melt is 1928, with an index runoff of 17.22 in. Entering the graph of Fig. 4 with this value (17.22 in.) indicates a melting rate of runoff of 0.0369 in. per degree-day on the enveloping line (as shown by the dashed line). This computed melting rate of runoff is selected as the maximum probable melting rate of runoff for computation of the maximum probable snow-melt flood.

8. The maximum probable snow-melt flood volume is computed by multiplying the melting rate of runoff (in this example 0.0369 in. per degree-day) by

the recorded maximum accumulative 15 days of mean temperatures above 32° F, as observed during periods of snow melt, adjusted to the basin. It is important that the maximum 15-day temperature accumulation be selected from a long period of record, preferably of at least twenty years. Lack of such a record within the basin usually necessitates transposing to the basin the most comparable long-term record available from a near-by point outside the basin. In the example cited, a maximum 15-day total of 377 degree-days, adjusted to the basin, was obtained. This accumulation of temperature would give 13.91 in. of snow-melt runoff, or 112,210 (cu ft per sec)-days.

Distribution of the design volume can be accomplished realistically by augmentation of the maximum, or near-maximum, 15-day recorded hydrograph by the ratio of the respective volumes. In this example, the 1921 runoff having the maximum 15-day volume of 77,120 (cu ft per sec)-days was

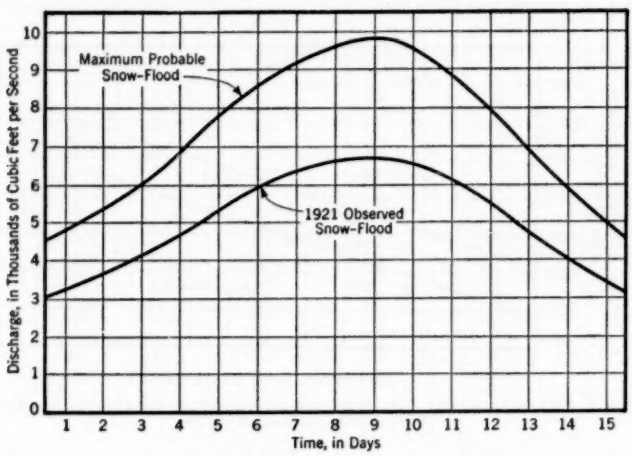


FIG. 5.—DESIGN SNOW-FLOOD HYDROGRAPH

augumented by the ratio of 112,210/77,120 to obtain the maximum probable snow-melt flood hydrograph shown in Fig. 5. Theoretical distribution of the design volume can also be accomplished by assuming that the maximum accumulative 15 days of mean temperature will follow a thermogram taken from the most severe temperature distribution of record. The runoff for each day, as computed from the daily temperature excesses of the thermogram and the melting rate of runoff, is distributed by a unit hydrograph derived from data such as those discussed previously. The total hydrograph is the sum of these daily flows.

*Flood Produced by Rain on Snow.*—In the high Sierra Nevada range of California, meterological conditions are such that the largest amounts of precipitation and the most severe floods usually occur during the months of November through March. Precipitation during these months can occur as rainfall at elevations up to 10,000 ft or 1,000 ft, and it is not unusual for a rain storm to

occur immediately after previous storms have deposited a cover of snow over the watersheds. The amount of runoff resulting from the rainstorm then depends on a delicate balance between the depth and the density of snow cover and the amount, intensity, and duration of the rainstorm. If a deep and "dry" snow cover exists, it may absorb and detain most of the rainfall, so that little runoff will result. On the other hand, with moderate snow cover and considerable intense rain, the snow cover temporarily "holds" rain until the snow melts, whereupon the "held" rain, plus the water content of the snow cover, is released rapidly, causing runoff exceeding that which would result from the rainstorm alone. The Sacramento River Basin floods of late November, 1950, are examples of this situation. In developing hydrographs for inflow design floods for dam sites located in this terrain, the critical consideration is the potential flood from an early winter rainstorm falling on a watershed having optimum snow cover. The snow-melt contribution may not be the dominant factor, but it is very significant in developing the inflow design flood. The melting rate of snow, the effect of the snow cover on the rain-fed runoff, and the losses into the soil are some of the problems to be resolved. An attempt was made early in 1951 to bring these factors together in a manner satisfactory for engineering applications in order to derive an inflow design flood for Sly Park Dam site, in the Central Valley Basin of California.

By applying the formula[8] of Phillip Light, A.M. ASCE, the Hydrometeorological section of the Weather Bureau (United States Department of Commerce) and the Corps of Engineers[9] (United States Department of the Army) had computed melting rates for watersheds within the Sacramento River Basin on the basis of turbulent transfer of heat and moisture between the air and the snow surface. As applied, relating the rate of melt over a drainage area to observation of wind velocity, temperature, and humidity at standard levels above the surface, the formula is

$$D = 0.00184\,K\,U\,(t - 32)\,10^{-0.0000156Z} + 0.00578\,(p - 6.11) \quad \ldots\ldots (3)$$

in which $D$ is melt, in inches of water per 6-hr period; $U$ is the wind velocity in miles per hour at the 50-ft level; $t$ is the temperature, in degrees Fahrenheit at the 10-ft level; $p$ is the vapor pressure, in millibars at the 10-ft level; $Z$ is the elevation, in feet above mean sea level; and $K$ is a regional or basin constant.

The merit of Mr. Light's formula has been demonstrated further by its application to snow-melt computations in connection with research conducted by the USBR in cooperation with the Forest Service (United States Department of Agriculture), at the Fraser Experimental Forest, at Fraser, Colo.[10]

Joseph B. Paulson, Jr., also had devised a method[11] of utilizing the Sacramento River Basin melting rates in such a manner as to provide increments of

[8] "Analysis of High Rates of Snow-Melting," by Phillip Light, *Transactions*, Am. Geophysical Union, Pt. I, 1941, pp. 195–205.

[9] "Maximum Possible Precipitation, Sacramento River Basin," *Hydrometeorological Report No. 3*, Weather Bureau, U. S. Dept. of Commerce, and Corps of Engs., U. S. Dept. of the Army, 1943.

[10] "Report No. 2, the 1949 Snowmelt Season, Progress in Snowmelt Investigations at the Fraser Experimental Forest, Colorado," Cooperative Snow Investigations, prepared and published jointly by the Bureau of Reclamation, U. S. Dept. of the Interior and Forest Service, U. S. Dept. of Agri., June, 1951.

[11] "A Method for Calculating the Effect of Snow on Runoff During a Rainstorm," by Joseph B. Paulson, Jr., *Transactions*, Am. Geophysical Union, Pt. 1, 1944, pp. 15–21.

"equivalent rainfall" that were mean values for the basin and that could be applied to some method of computing a rain-runoff hydrograph. The Sacramento District office of the Corps of Engineers, in computing the inflow design flood for Pine Flat Dam on Kings River,[12] had made use of Mr. Paulson's method as modified to provide for the effect of a varying infiltration rate.

In the study of Sly Park damsite on Sly Park Creek, a northern tributary of the Mokelumne River, California, made by the USBR, the basic assumptions of the foregoing methods were re-examined in view of observations reported in November, 1950, at the Central Sierra Snow Laboratory, near Soda Springs, Calif., by D. H. Miller, J. M. ASCE, of the Corps of Engineers. The drainage area of 16 sq miles above Sly Park ranges in elevation from about 3,300 ft to nearly 5,800 ft. Three elevation zones were considered: One beween 3,000 ft and 4,000 ft containing 57.5% of the area; one between 4,000 ft and 5,000 ft, containing 34.9% of the area; and one between 5,000 ft and 6,000 ft, representing 7.6% of the area. The watershed was assumed to be covered by snow from a storm which shortly preceded the design rainstorm. Hydrometeorological studies[9] indicated 12 hr as the minimum interval possible between the end of a snowstorm and the beginning of a maximum probable rainstorm. Table 3 lists the water content in inches of assumed antecedent snow cover from *Hydrometeorological Report No. 3*,[9] the assumed density (explained subsequently), and the depth of snow in inches by elevation zones at the time rainfall would begin.

TABLE 3.—DESCRIPTION OF SNOW COVER

| Elevation band, in feet | Water content, in inches | Density, in % | Snow depth, in inches |
|---|---|---|---|
| 3,000–4,000 | 6.00 | 17 | 35.30 |
| 4,000–5,000 | 5.10 | 16 | 31.86 |
| 5,000–6,000 | 3.60 | 15 | 24.00 |

The snow on the ground preceding the rain was "new-fallen." Density of new-fallen snow varies, but only on rare occasions does it reach 20%. According to Mr. Miller, the snowfall density on November 16, 1950, with a temperature of 30° F, at the Central Sierra Snow Laboratory (elevation approximately 7,000 ft), was over 13%. For the Sly Park study, it was assumed that, under maximum probable conditions, density of the new snow would vary uniformly from 20% at El. 1000 to 10% at El. 10000.

An accumulation of 1.5 in. of melt water was assumed to have been retained on the watershed before the beginning of the inflow design flood computations. Additional retention during the rain and melt period was taken from a curve plotted in such a manner that 6-hr increments of retention were indicated from total accumulative retention. Only the application of values from this curve is pertinent to the present discussion.

The data of Table 3 were then utilized as follows: During the 6-hr period preceding the design rain a small amount of melting begins as the result of rising temperatures. As the design rain starts, melting of the snow cover is accelerated by warmer temperatures and turbulence from accompanying winds. The water initially released by melting and from rain is stored in the

[12] *Corps of Engineers Definite Project Report*, Pine Flat Dam and Reservoir, Kings River, Calif., April, 1947.

snow pack.[13] The density of the snow pack increases and its actual depth decreases as the process continues. When the density reaches the retention-capacity limit of the snow pack, the excess water will be released either to infiltration or runoff. The snow pack will attain a "saturated" density and will

TABLE 4.—Analysis of Rainfall on Snow Having an Assumed Initial Density of 17%; for the Elevation Zone Between 3,000 Ft and 4,000 Ft in the Sly Park Study

Procedure:

Col. 3 is taken directly from storm data.
Col. 4 represents potential snow melt, and is computed from Eq. 3 using observed data.
Col. 5 is obtained from Col. 4 by dividing those values by the values in Col. 7 for the preceding period.
Col. 6 begins with the value of the depth of the antecedent snow cover (the given water content divided by 17%). Each subsequent value is obtained from the preceding value by adding the depth of any new snowfall (not applicable to this example) and subtracting the value in Col. 5.
Col 7 is computed by dividing the values in Col. 9 by those in Col. 6.
Col. 9 begins with the value of the water content of the antecedent snow cover. Subsequent values are obtained from the preceding value in Col. 14 by adding the value in Col. 3 (plus snowfall, if applicable).
Col. 10 shows the excess of values in Col. 9 over those in Col. 8, or the values from the retention curve, whichever are smaller.
Col. 11 shows the accumulation of values in Col. 10.
Col. 12 is obtained by subtracting the values in Col. 10 from those in Col. 9.
Col. 13 is the excess of each value in Col. 12 over the corresponding value in Col. 8.
Col. 14 is obtained by subtracting the values in Col. 13 from those in Col. 12, and cannot exceed corresponding values in Col. 8.
Col. 15 is equal to Col. 13 multiplied by the ratio of the band area to the total basin area (0.575 for this band).

| 6-Hr Time Increment | | Increment of rain, in inches | Increment of Snow Melt, in Inches | | Depth of snow on the ground,[a,b] in inches | Density of the snow,[c] in % | Water-holding capacity at 40% density,[d] in inches | Accumulated unreduced water content,[e] in inches | Increment of retention, in inches | Accumulated retention,[f] in inches | Accumulated reduced water content,[g] in inches | Increment of water excess, in inches | Residual water content,[h,b] in inches | Contribution to the basin mean water excess, in inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Start | End | | Water content | Depth | | | | | | | | | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) |
| | | | | | 35.30 | 17 | 14.12 | 6.00 | 0 | 1.50[i] | 6.00 | 0 | 6.00 | 0 |
| −6 | 0 | | 0.4[j] | 2.35 | 32.95 | 18.2 | 13.18 | 6.00 | 0 | 1.50 | 6.00 | 0 | 6.00 | 0 |
| 0 | 6 | 1.4 | 1.00 | 5.49 | 27.46 | 27 | 10.98 | 7.40 | 0 | 1.50 | 7.40 | 0 | 7.40 | 0 |
| 6 | 12 | 2.4 | 1.00 | 3.70 | 23.76 | 40 | 9.50 | 9.80 | 0.3 | 1.80 | 9.50 | 0 | 9.50 | 0 |
| 12 | 18 | 3.7 | 1.20 | 3.00 | 20.76 | 40 | 8.30 | 13.20 | 1.77 | 3.57 | 11.43 | 3.13 | 8.30 | 1.80 |
| 18 | 24 | 1.0 | 0.70 | 1.75 | 19.01 | 40 | 7.60 | 9.30 | 1.50 | 5.07 | 7.80 | 0.20 | 7.60 | 0.12 |
| 24 | 30 | 0.3 | 0.70 | 1.75 | 17.26 | 40 | 6.90 | 7.90 | 1.00 | 6.07 | 6.90 | 0 | 6.90 | 0 |
| 30 | 36 | 4.8 | 1.60 | 4.00 | 13.26 | 40 | 5.30 | 11.70 | 1.20 | 7.27 | 10.50 | 5.20 | 5.30 | 2.99 |
| 36 | 42 | 7.2 | 2.00 | 5.00 | 8.26 | 40 | 3.30 | 12.50 | 1.03 | 8.30 | 11.47 | 8.17 | 3.30 | 4.70 |
| 42 | 48 | 5.4 | 1.60 | 4.00 | 4.26 | 40 | 1.70 | 8.70 | 0.90 | 9.20 | 7.80 | 6.10 | 1.70 | 3.51 |
| 48 | 54 | 3.4 | 1.20 | 3.00 | 1.26 | 40 | 0.50 | 5.10 | 0.77 | 9.97 | 4.33 | 3.83 | 0.50 | 2.20 |

[a] Cannot be less than zero. [b] The depth of snow left at the end of the storm (last line) equals 1.26 in., with a water content of 0.50 in.; if melted in the following 6-hr period, this quantity would be absorbed by retention. [c] Holding capacity of the snow mass, not to exceed 40%. [d] Maximum capacity of the snow mass to prevent significant retention. [e] The accumulated water content unreduced for retention or surface runoff during the period. [f] Used as a parameter for retention capacity. [g] The accumulated water content after reduction for retention during the period. [h] Total water content carried forward into next period. [i] Assumed initial accumulated retention. [j] Melting preceding design rain.

continue to decrease in depth during infiltration and runoff until the storm ends and temperatures fall below 32° F. If snow remains at the end of the storm, it will have a density equal to that at which it ceased to store water.

[13] "A New Technique for the Determination of Heat Necessary to Melt Snow," by Merrill Bernard and Walter T. Wilson, *Transactions*, Am. Geophysical Union, 1941, Pt. I, pp. 178–181.

According to Mr. Miller, during the flood of November, 1950, the snow remaining on the ground after approximately 16 in. of rain had fallen upon it had a density of from 40% to 45%.

In the Sly Park study, it was assumed that no release of water from the snow pack would occur until the snow attained a density of 40%, and that all water in the snow pack above a density of 40% would be available to infiltration and runoff. Table 4 shows the computation for the zone between 3,000 ft and 4,000 ft. If snow had fallen during the storm, it would have been necessary to add a column between Cols. 2 and 3, entitled "Increment of Precipitation," and two columns to the left of Col. 4, under the general heading, "Increment of Snowfall." The first column under this general heading would have shown the water content and the second the depth of the snow, the second set of values having been obtained by dividing all the water-content values by 17%, the assumed initial density. These values affect those in Col. 6. If snow had fallen at the end of the storm, runoff would have stopped.

Addition of the values of the contributions to the mean water excess for the basin (Col. 15, Table 4), computed from each elevation band, provided incremental runoff values that were applied to a unit hydrograph for the watershed in order to determine the hydrograph for the inflow design flood.

*Inflow Design Flood Based on Seasonal Snow Melt.*—Safe utilization of joint-use storage space for the control of the inflow design flood in areas where the snow flood is dominant can be assured by the development of an inflow design flood portraying maximum probable snow-melt runoff from the beginning of the melting season to its cessation and including runoff from a rainstorm that reasonably could be expected to occur concurrently with, or immediately following, the high discharges from melting snow.

Numerous methods exist by which such a seasonal hydrograph can be developed. Fundamentally, they are all based on the concept of a winter of high snowfall and continuing low temperature, followed by a period of unusually high temperature, and accompanying rainfall which produces maximum rates and volumes of runoff from the melting of the accumulated snow pack. The 1948 flood of the Columbia River[14] was an actual example of this type of event.

In January, 1951, Bertram S. Barnes, M. ASCE, working with data from the South Fork Flathead River in Montana (an upper tributary of the Columbia River) developed a procedure utilizing observed temperature sequences to compute favorable reproductions of observed seasonal runoff. This procedure of the USBR is being expanded for application in deriving the maximum probable flood. Mr. Barnes' procedure involves the following major steps and assumptions:

1. A "base" temperature can be derived, which, when subtracted from the maximum daily temperatures at a near-by observation station during an observed snow flood, will give the best index of melting temperatures over a watershed.

2. The direct runoff occurring during the snow flood will reflect the index of melting temperatures. Direct runoff is observed runoff from which groundwater flow has been subtracted by standard methods.

[14] "Floods of May–June 1948 in Columbia River Basin," *Water-Supply Paper No. 1080*, U. S. Geological Survey, U. S. Dept. of the Interior, Washington, D. C., 1949.

3. Before index melting temperatures will be properly reflected in a reproduction of the computed direct runoff, the proper base temperature must be determined by trial and error. This is done by using a device referred to as the "hydrothemogram."

4. The hydrothermogram is a hypothetical discharge hydrograph computed on the assumption that each effective degree of temperature above the base temperature will generate the same amount of runoff volume. Of this runoff volume, the maximum daily runoff occurs on the first day, thereafter decreasing at a normal rate such as illustrated in Fig. 1. The runoff on the first day is assumed to be one unit per degree of temperature. The second day's runoff from that same generation is the depletion factor (0.816 for the South Fork Flathead River) times the runoff for the first day; the third day is the depletion factor times the runoff for the second day; and the values for succeeding days are computed in the same way. For a given sequence of daily effective temperatures above a given base, the process is similar to that approach

TABLE 5.—COMPUTATIONS FOR A HYDROTHERMOGRAM

| Date, in April | Maximum temperature (in degrees) above 54° | Residual,* in (cubic feet per second)—days | Total daily runoff, in (cubic feet per second)—days |
|---|---|---|---|
| (1) | (2) | (3) | (4) |
| 14 | 2 | .... | 2.0 |
| 15 | 8 | 1.6 | 9.6 |
| 16 | 15 | 7 .8 | 22.8 |
| 17 | 3 | 18.6 | 21.6 |

* The previous total from Col. 4 multiplied by the depletion factor, 0.816.

which involves unit hydrographs for successive unit periods of excess rainfall. The sample computations in Table 5 are from one of the work sheets, starting at the beginning of the snow-melt season.

In reproducing an observed seasonal hydrograph with a recorded temperature sequence, the procedure is applied with successive base temperatures until the best fit is obtained between the hydrothermogram and the hydrograph of direct runoff. The melting rate of runoff necessary to convert the thermogram to the observed runoff becomes apparent at this stage of the analysis. Fig. 6(*a*) shows the hydrograph of direct runoff for the South Fork Flathead River during April and May, 1948, and the derivation of the daily depletion factor. Fig. 6(*b*) demonstrates the comparison of hydrothermograms for differing base temperatures with this hydrograph of direct runoff. The base temperatures are noted on the curves. A base temperature of 57° F provided the best fit.

Application of the base temperature, the maximum melting rate of runoff, and the hydrothermogram—in order to determine the maximum probable snow flood hydrograph—requires prediction of the design snow-flood volume and of the melting period. The design volume can be computed by several procedures from an estimate of the maximum probable snow pack which would accumulate during a cold winter of heavy snowfall. The total design volume may then be divided into two parts: The direct runoff which follows the

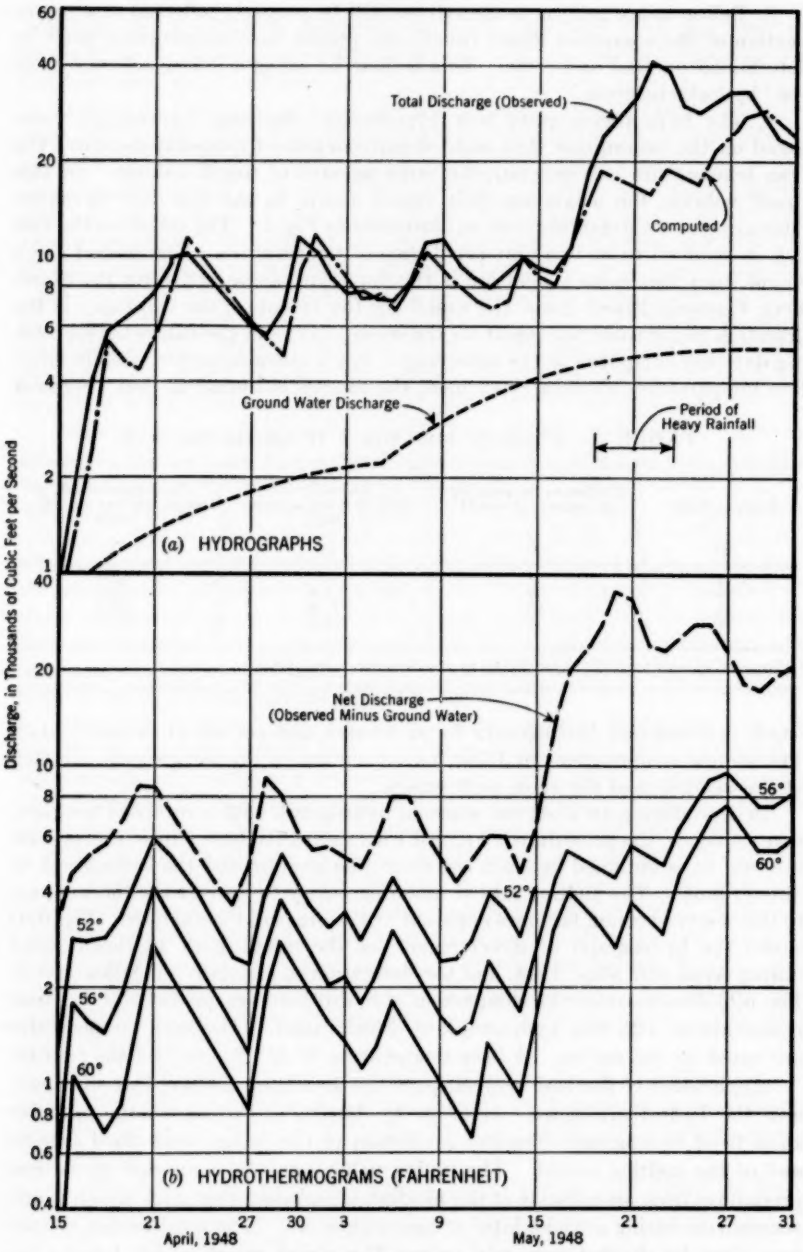


FIG. 6.—RUNOFF, SOUTH FORK FLATHEAD RIVER

thermogram pattern and the direct runoff in the hydrograph recession. Proportioning the design volume into these two parts is done by analyzing several observed hydrographs. The volume falling into each of the two parts may then be expressed as a percentage of the total direct runoff. The hydrothermogram of the maximum probable temperature sequence and the maximum melting rate of runoff are then applied until the first part of the design volume is satisfied.

## Conclusions

The economic necessity for full development of the water resources of the western states can be accomplished only by taking advantage of every opportunity for full utilization of the limited stream flows. The construction of multiple-purpose reservoirs on surface streams is one of the most common methods for attaining this objective. In the determination of space allocation for each of the multiple uses and spillway capacities of multiple-purpose resevoirs, economy can be obtained by considering stream-flow and snow-melt characteristics. This paper has presented a summary of the principles involved and a few typical examples. No attempt has been made to cover the subject historically or in full detail. Those interested will find such detail available in the published reports of the agencies engaged in such planning and design. Great refinement in procedure, with corresponding economy in both design and operation, will result from continued research in the field of snow hydrology and from the extension of networks for the collection of data so that they include pertinent elements on a watershed basis.

## Acknowledgments

The specific examples given herein have been taken from the files of the Hydrology Branch, Project Planning Division of the USBR. Many of the procedures have been developed from data-gathering and research activities in collaboration with the Corps of Engineers, the U. S. Weather Bureau, and the Soil Conservation Service (United States Department of Agriculture) and the Forest Service.

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